Cihat Okan Arikan[1], Samet Doğan[2], Deja Muck[3]
[1] Ege Üniversitesi, Emel Akın Vocational School, 35100, Bornova/İzmir
[2] Ege University, Faculty of Engineering, Textile Engineering, Erzene, 35100 Bornova/İzmir
[3] University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Textiles, Graphic Arts, and Design, Snežniška 5, 1000 Ljubljana, Slovenia

Geometric Structures in Textile Design Made with 3D Printing

Geometrične strukture v tekstilnem oblikovanju, izdelane s 3-D tiskom

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 11-2022 • Accepted/*Sprejeto* 12-2022

Corresponding author/*Korespondenčni avtor:*
Samet DOĞAN
E-mail: sametdogan1299@gmail.com
ORCID ID: 0000-0002-3988-6799

Abstract
3D printing is a well-known technology for producing 3D objects by depositing successive layers of material. Among its many applications, the fashion industry has taken advantage of this technology to revolutionize its brands. Due to the unique properties of textiles, such as comfort, flexibility, etc., attempts have been made to create textile-like structures. Structures with different geometries were designed and printed using different materials ranging from rigid to flexible. In this study, three different basic geometric structures were designed using the Blender program (a free open-source 3D modelling software). Each geometric structure was designed in two different sizes with smaller and larger basic structural elements. In this case, six different models were created. The aim of this study was to compare the textile-like surfaces of different basic geometric shapes produced with 3D printers. It also aimed to investigate the use of surfaces designed with basic geometric shapes in the textile-like material for fashion industries. In the production phase, the fused deposition modelling (FDM) process was chosen, and ABS and TPU materials were used. Various tests were performed, such as mass tests, and tensile and flexural strength tests on models with different basic geometric shapes and sizes. An examination of the test results showed that the different geometric shapes of the various basic structures and the different materials used have an overall effect on the final properties of the structures. It was concluded that the obtained results can be used as a reference and could be helpful for researchers in the use of 3D printers in the textile-like material and fashion material industries.
Keywords: 3D printing, geometric structures, textile-like material design

Izvleček
3-D tiskanje je že dobro poznana tehnologija za izdelavo 3-D objektov z nanosom zaporednih slojev materiala. Med številnimi aplikacijami je tudi modna industrija to tehnologijo izkoristila za revolucioniranje svojih blagovnih znamk. Zaradi edinstvenih lastnosti tekstilij, kot so udobje, fleksibilnost itd., se poskušajo ustvariti tekstilu podobne strukture. V raziskavi so bile oblikovane strukture z raznovrstnimi geometričnimi vzorci in natisnjene z uporabo različnih materialov, od togih do fleksibilnih. S programom Blender (odprtokodna programska oprema za 3-D modeliranje) so bile modelirane tri različne osnovne geometrične strukture. Vsaka geometrična struktura je bila zasnovana v dveh različnih

velikostih z manjšimi in večjimi osnovnimi konstrukcijskimi elementi. Tako je nastalo šest različnih modelov. Cilj študije je bil primerjati tekstilu podobne površine različnih osnovnih geometričnih oblik, izdelanih s 3-D tiskalniki. Prav tako študija želi raziskati uporabo površin, oblikovanih z osnovnimi geometrijskimi oblikami, v materialih za modno industrijo. Za izdelavo geometričnih struktur je bil izbran postopek modeliranja s spajanjem slojev (FDM) in uporabljena materiala ABS in TPU. Na modelih z različnimi geometričnimi oblikami in velikostmi so bile opravljene različne meritve, kot so meritve mase in meritve natezne in upogibne trdnosti. Analiza rezultatov testiranja je pokazala, da različne geometrijske oblike različnih osnovnih struktur in različni uporabljeni materiali močno vplivajo na končne lastnosti omenjenih struktur. Ocenjujemo, da so dobljeni rezultati lahko dobra referenca in pomoč raziskovalcem pri uporabi 3-D tiskalnikov na področju oblikovanja tekstilu podobnih materialov v modni industriji.
Ključne besede: 3-D tisk, geometrične strukture, oblikovanje tekstilu podobnih materialov

1 Introduction

The use of computer technologies in the design stages of the textile sector, as well as the use of new materials and production methods in design, bring a new approach to the design creation process. Textile surface designs have been developed by using new developments in design and production areas and materials developed for different purposes. 3D printers are one of the innovative processes that are claimed to lead to the industry 4.0 revolution. 3D printers allow the production of objects without the use of tools [1]. Textile and apparel designs developed in recent years have been influenced by technology and all the developments in design and production and have been produced using many materials and techniques developed for different purposes [2].

Various 3D production methods can be used for printing textile-like materials in the fashion industry. The most preferred methods are SLA (stereo lithography), SLS (selective laser sintering), FDM (fused deposition modelling) and Polyjet 3D [3].

We focused primarily on FDM as the most frequently used technology, as we found many interesting articles about the aforementioned process. It has been shown that the choice of pattern and material affects the properties of material surfaces. This study showed that the larger the pattern, the harder the textile-like surface becomes (Figure 1). The size of a repeating pattern also has a significant impact on the printing time of the pattern. The smaller the pattern, the longer the printing process will take. The flexibility of the surface can also be affected by the number of layers and especially the number of connecting wires. The more connecting wires a structure contained, the harder the surface became (Figure 2 A–C), while the tensile strength of the structure increased. In this study, a good compromise between the flexibility, elasticity and tensile strength of the textile-like surface was identified with a compression model consisting of 11 layers (Figure 2C) [4].

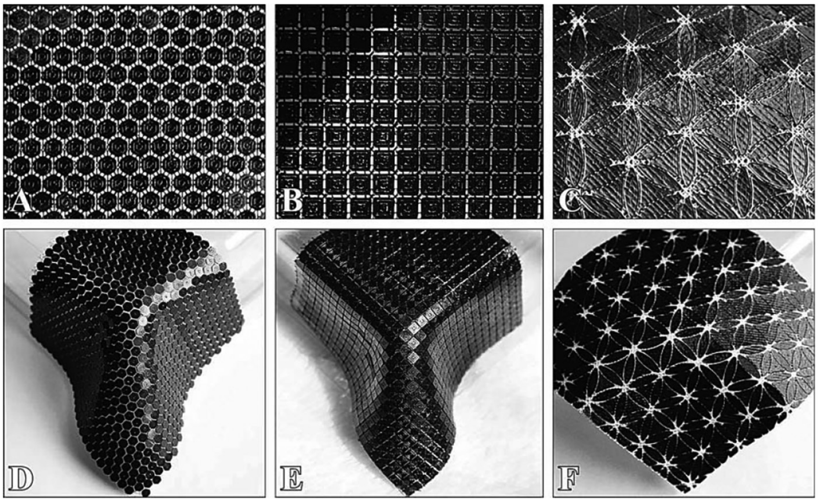


Figure 1: Illustration of various repeating patterns: A) polygon pattern, B) rectangle pattern, C) floral pattern, D) fabric-like curtain with polygon pattern, E) fabric-like curtain with rectangle pattern, F) curtain with large patterns [4]

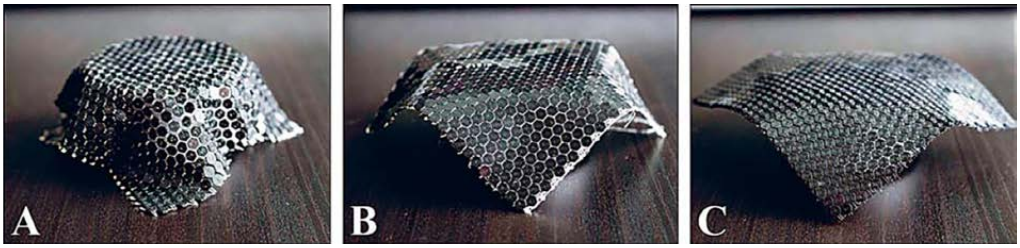


Figure 2: Different flexibilities based on the number of layers: A) five layers (three layers of PLA, two layers of LAY-FOMM 40), B) seven layers (four layers of PLA, three layers of LAY-FOMM 40), C) 11 layers (six layers of PLA, fives layers of LAY-FOMM 40) [4]

An important aspect of this work was to ensure the comfort of use of the textile-like surfaces. These properties can be achieved with the flexible and elastic printing material LAY-FOMM 40. Since LAY-FOMM 40 is harmless and food-safe according to the manufacturer, four layers of LAY-FOMM 40 are printed on each model (Figure 3). Basically, this is a printed lining layer that is also incorporated into conventional clothing. Special effects can be achieved by manually intervening in the Z-height of a layer during the printing process [4].

In collaboration with a PhD project at the University of Central Florida in Orlando, a glove with integrated sensors based on textile-like structures was printed (Figure 4). Sewing patterns were developed for the glove that are also used in the textile industry to produce garments (Figure 4A). It was printed using a X400 3D printer and PLA and LAY-FOMM 40 materials. As Figures 4B and 4C show, the surface of the glove was partially printed with polygons [4].

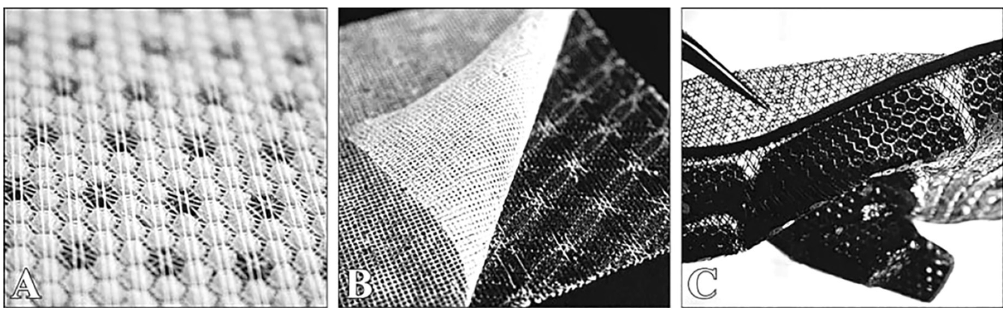


Figure 3: Printed lining: A) four layers of LAY-FOMM 40 on textile-like surface, B) and C) fusion of four layers[4]

Figure 4: 3D printed glove: A) sewing pattern printed from two materials, B) surface design of the glove, C) flexible sewing pattern with inner lining, D) pattern parts sewn together to form a three-dimensional garment [4]

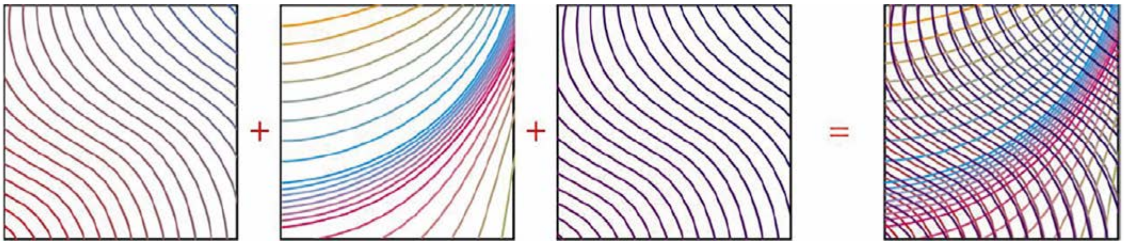


Figure 5: Test pattern for a layered structure consisting of three superimposed layers [5]

In the glove pattern, several layered structures were achieved using FDM technology [5]. Figure 5 shows a test structure used to investigate whether individual strings can be applied to relatively open structures without support structures [5].
The results of the FDM print in Figure 6 show that while this approach is mostly successful, the threads can sometimes break, even when a minimum diameter of 0.4 mm is maintained. Therefore, lace-like structures were created that also start with a partially open base layer but do not contain free-floating regions as the next approach to creating textile-based 3D printed patterns [5].

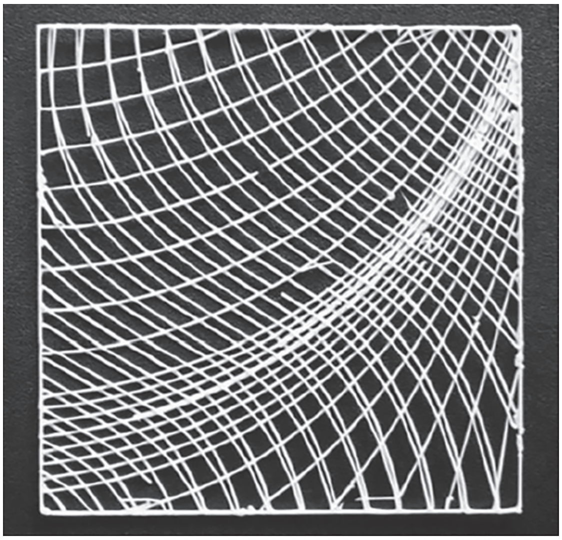
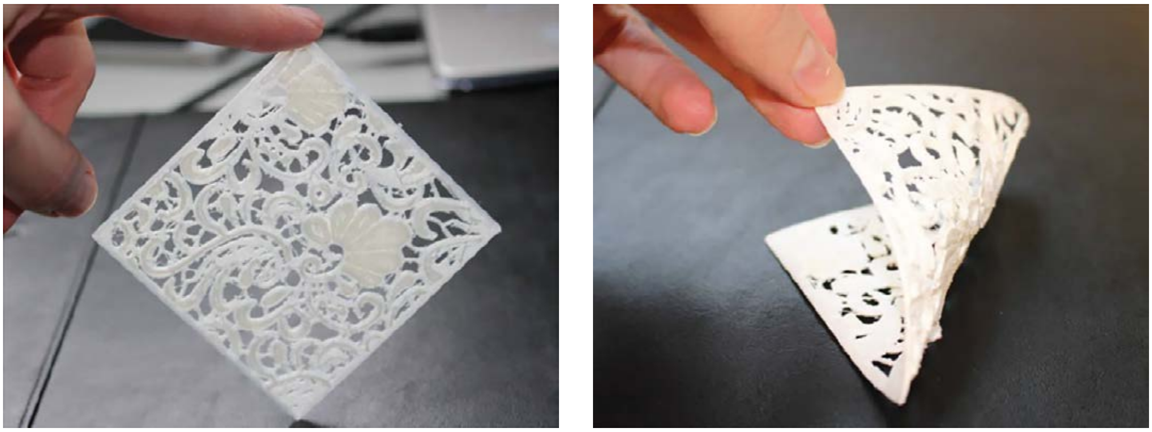


Figure 6: Results of the 3-layer structure printed using FDM (size 8 cm × 8 cm) [5]

Based on the well-known Plauen lace, lace patterns were designed, usually containing floral and circular elements on a base layer connecting these parts. One such pattern is shown in Figure 7a. Since there are no free-floating areas, printing using the FDM process is not problematic if all connecting lines have a sufficiently large diameter (Figure 7b) [5].
In addition to soft PLA, which was used for most of the lace patterns to avoid potential mechanical problems with harder material that could cause base joints to break, an experimental polymer was used: Lay Tekkks, one of four different types of porous filament from the PORO-Lay line. Lay Tekkks is a hard filament manufactured by Kai Parthy of CC-Products (Cologne, Germany) that can be transported to the nozzle without the transport problems that too-soft filaments can cause in some FDM printers. However, after printing is complete, it can be placed in warm water for a period of minutes to hours, which causes the hard part of the material to dissolve. The resulting sample thus becomes increasingly softer the longer it is immersed in water (Figure 8) [5].


a) b)
Figure 7: Multi-layer lace pattern shown in 'netfabb' (a), and the resulting 3D print (b). Detail size ~ 4 cm × 7 cm [5]



a) b)

Figure 8: Lace pattern from Lay Teks before (a) and after dissolving the hard material in warm water for three hours (b). The size of the pattern is 8 cm × 8 cm [5]

The aim of this study was to print textile-like surfaces with different geometric structures using 3D printing technologies based on thermoplastic extrusion. A fused deposition modelling (FDM) was used as the 3D production method. In this study, 6 different models were designed using 3 different basic geometric structures. These are small size hole square, large size hole square, small size hole triangle, large size hole triangle, small size hole hexagon, large size hole hexagon. All of the modeled samples were printed in the same size. Only the hole sizes and shapes of the models were different. These 6 different models were printed with ABS and TPU material. Three different tests were applied to total 72 samples. The effects of these basic geometric shapes on textile-like surfaces were investigated using mass, tensile and flexural strength measurements. In the study, it was also investigated which basic geometric shape is more useful and flexible in textile-like materials; which basic geometric structure could be more durable and what could affect the test results; and which thermoplastic material and basic geometrical structure can exhibit properties like a textile-like fabric.

2 Materials and methods

2.1 Sample preparation

2.1.1 ABS and TPU

ABS (also known as acrylonitrile-butadiene-styrene) has high hardness, good impact strength even at low temperatures, good insulating properties, good wear and tensile strength, high dimensional stability, and high surface gloss [6, 7].

Thermoplastic polyurethane (TPU) is a melt-processable thermoplastic elastomer with high durability and flexibility. TPU offers a wide range of physical and chemical property combinations for the most demanding applications, e.g., automotive, wire and cable, breathable films for leisure, sports and textile coatings, wearable non-yellowing films, etc. Its properties are between the characteristics of plastic and rubber. Thanks to its thermoplastic characteristic, it has several advantages that other elastomers cannot offer, such as excellent tensile strength, high elongation at break and good load-bearing capacity [8, 9].

2.1.2 Modelling of geometric structures

In this study, textile-like surfaces were printed based on three different basic geometric shapes: square, triangle and hexagon.

2.1.3 Printing

The printed models in this project were made using a Zmorph FAB 3D printer (Zmorph, Poland) (Figure 9), which uses the fused deposition modelling process. This high-quality semi-professional 3D printer processes thermoplastic filaments by melting them in the extruder immediately before printing. The maximum operating temperature at the extruder tip is 260 °C, while the maximum extrusion volume is 40 mm/s. The maximum working volume of the printer is 235 mm ×250 mm ×165 mm. The printer uses Voxelizer printing software. A file in Voxelizer format is transferred to the printer via a

USB memory stick or Wi-Fi. FDM is a process based on the formation of a new layer on another layer by melting the fibrous thermoplastic material.

The printing material used in this project was an ABS (acrylonitrile butadiene styrene) filament (AzureFilm, Slovenia), which is a lightweight, high-impact and high-creep polymer [10]. TPU (thermoplastic polyurethane) (AzureFilm, Slovenia) with high tensile strength was also used.

This system is based on the principle of extruding molten plastic from a heated injector onto a heated moving bed [11]. To obtain the model after printing from the pressure bed, the temperature of the bed must be lowered to a minimum temperature of 30 °C degrees.

The parameters used to print the models in this study on the Zmorph 3D printer are shown in Table 1 for ABS material and Table 2 for TPU material.

Figure 9: Photo during printing

Table 1: Printing parameters for printing with ABS material

Settings	Value
Extruder settings	
Default print speed	24 mm/s
Travel speed	90 mm/s
Layer settings	
First layer speed	40%
First layer height	0.42 mm
Maximum adhesion ratio	2.5
Height minimum multiplier	0.4
Height maximum multiplier	0.75
Temperature	
Hotbed temperature	100 °C
Extruder temperature	255 °C
Fan speed	40%
Other	
Filament diameter	1.75 mm
Extrusion diameter	m

Table 2: Printing parameters for printing with TPU material

Settings	Value
Extruder settings	
Default print speed	20 mm/s
Travel speed	120 mm/s
Layer settings	
First layer speed	100 %
First layer height	0.25 mm
Maximum adhesion ratio	2.25
Height minimum multiplier	0.3
Height maximum multiplier	0.85
Temperature	
Hotbed temperature	60 °C
Extruder temperature	250 °C
Fan speed	30 %
Other	
Filament diameter	1.75 mm
Extrusion diameter	m

2.1.4 Software

The models created in this study were modelled using the 3D Blender program. The modelled patterns are saved as *.stl files and transferred to the Voxelizer software for 3D printing. A *.stl file is easy to use for printing with this program. A G-code file is also created to transfer the models to the printer with the Voxelizer program for special head and print movements.

2.1.5 Models printed with ABS and TPU

To ensure the comparability of the test results, the sizes of the models were designed in basic geometric shapes that were most similar to each other. The models were designed on the basis of the dimensions 50 mm × 150 mm × 2 mm, so that they could be easily tested in a tensile and bending testing machine. The width of the lines forming the geometric shapes was 0.8 mm.

2.2 Samples

Sample 1

(a) Small size hole square

The width of all lines forming the figures in the patterns was 0.8 mm. The dimensions of this pattern, created in the form of small squares of horizontal and vertical lines, were 49.4 mm × 151.42 mm × 2 mm. The inner dimension of each square was 4.5 mm × 4.5 mm. A real, printed 'small size hole square' example is shown in Figure 10, while the 3D model drawing made using Blender software is shown in Figure 11.

(b) Large size hole square

The size of this model was 49.4 mm × 153.9 mm × 2 mm. However, in this example, the dimensions of the square holes were larger than in the previous model. In this model, the x and y length of the inner square was 8.8 mm × 8.8 mm. A real 'large size hole square' example is shown in Figure 12, while a 3D model drawing made using Blender software is shown in Figure 13.

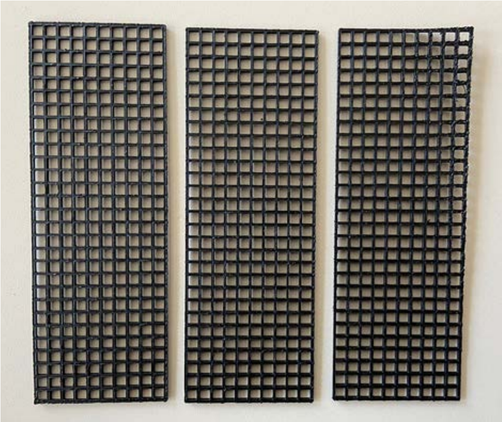


Figure 10: Structures printed with ABS small size hole square

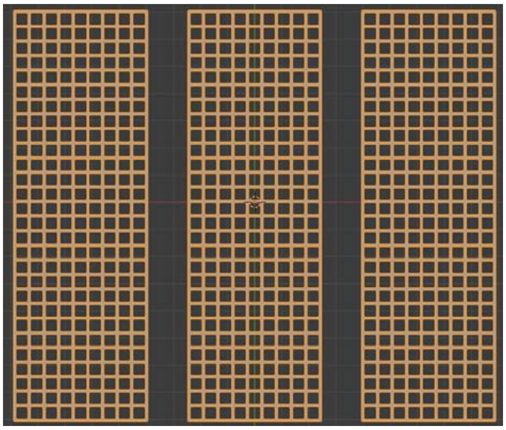


Figure 11: Screenshot of the 3D modelled square structure with small holes in Blender software

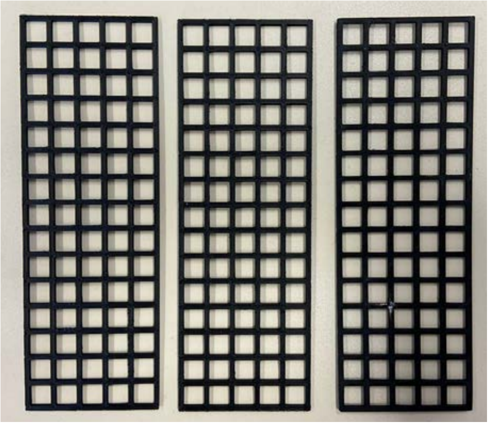


Figure 12: Structure printed with ABS large size hole square

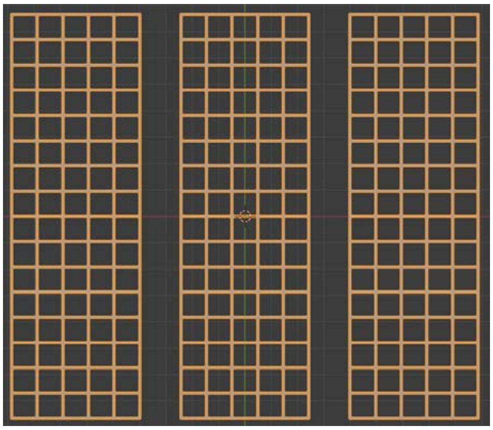


Figure 13: Screenshot of the 3D modelled large size hole square structure in Blender software.

Sample 2

(a) Small size hole triangle

In this model, small triangles with only one diagonal were formed on the small squares of the first example (Figure 14). The dimensions of this model were 49.4 mm × 151.2 mm × 2 mm. The 3D model prepared using Blender software is shown at Figure 15.

(b) Large size hole triangle

The size of this model was 49.4 mm × 153.9 mm × 2 mm. This model is similar to the small size hole triangle model. The model size was made larger and is shown in Figure 16, while 3D the drawing model using Blender software is shown in Figure 17, The difference in size and triangular area was obtained by adding a diagonal to each square.

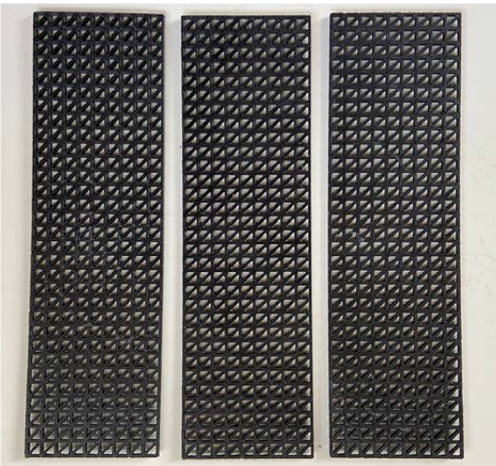


Figure 14: Structure printed with ABS small size hole triangle

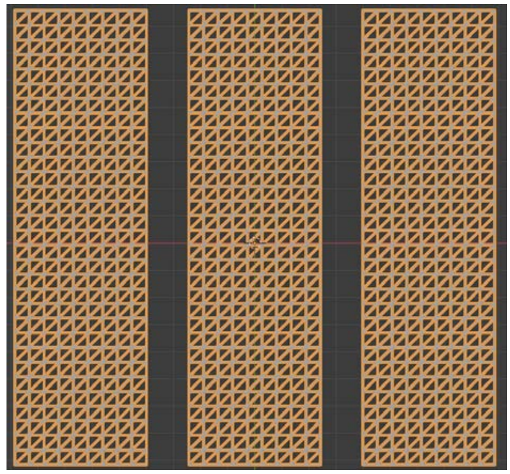


Figure 15: Screenshot of the 3D modelled small size hole triangle structure in Blender software

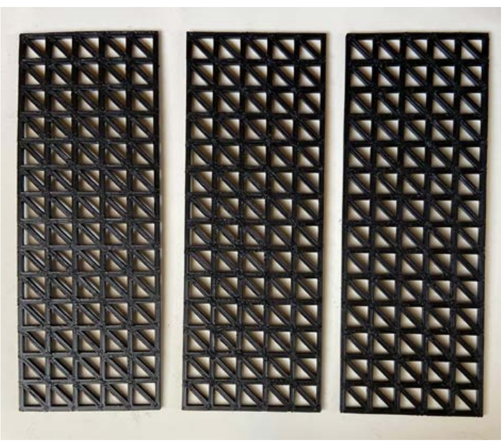


Figure 16: Structure printed with ABS large size hole triangle

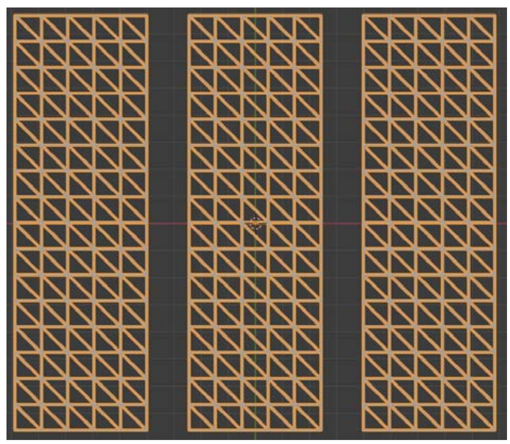


Figure 17: Screenshot of the 3D modelled large size hole triangle structure in Blender CAD software

Sample 3

(a) Small size hole hexagon

This model had a large diagonal dimension of 6.11 mm. The dimensions of this model were 51.8 mm × 147.7 mm × 2 mm. The real structure is shown in Figure 18, while the 3D model prepared using Blender software is shown in Figure 19.

(b) Large size hole hexagon

This model was designed with large hexagonal shapes with a large diagonal length of 12.22 mm. The dimensions of this model were 54.7 mm × 150.7 mm × 2 mm. This is similar to the small size hole hexagon model, but with larger sized holes. The real structure is shown in Figure 20, while the 3D model prepared using Blender software is shown in Figure 21.

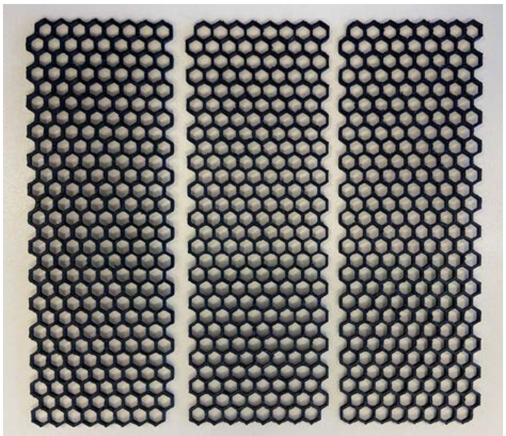


Figure 18: Structure printed with ABS small size hole hexagonal

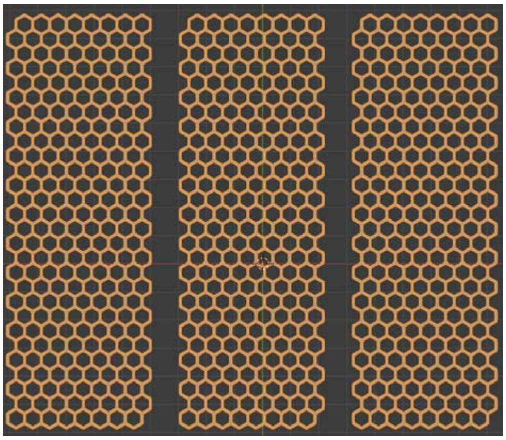


Figure 19: Screenshot of the 3D modelled small size hole hexagonal structure in Blender software

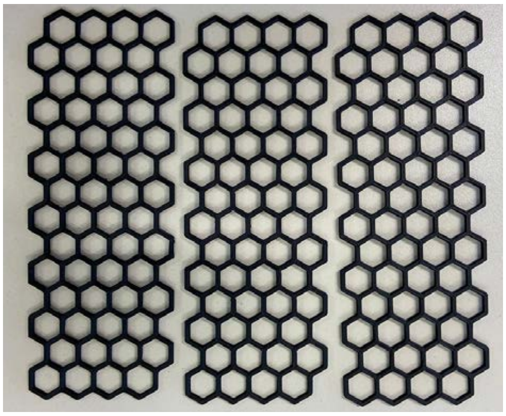


Figure 20: Structure printed with ABS large size hole hexagonal

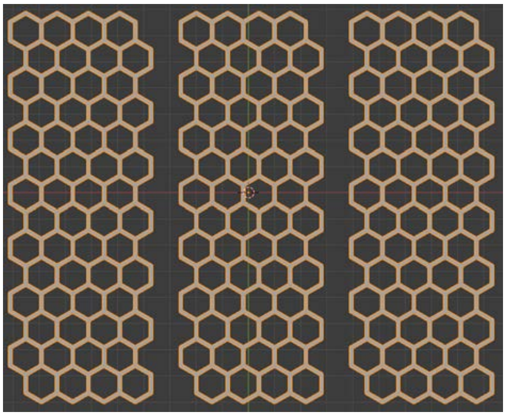


Figure 21: Screenshot of the 3D modelled large size hole hexagonal structure in Blender software

2.3 Methods

A mass of samples that were designed in similar dimensions was tested to understand effects of printed ABS and TPU materials in six different ways. The mass of the samples was measured with precision balance Mettler Toledo AE 200.

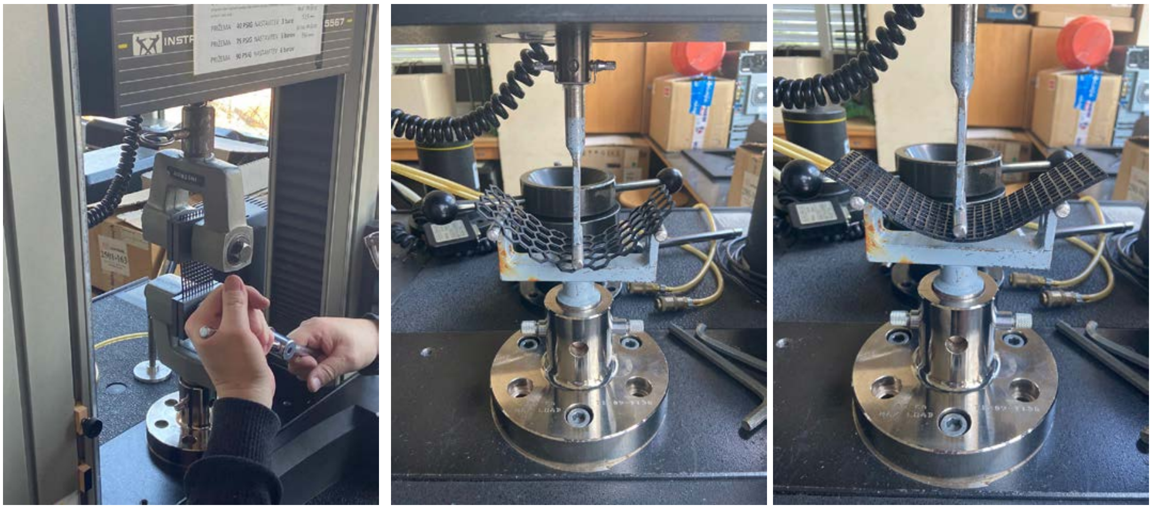
Mechanical properties have been tested on a dynamometer Instron 5567 (Instron, GB) (Figure 22a). The distance between the clamps was 5 cm. Tensile test applied to the samples with six different textile-like surfaces with three different basic geometric structures produced using ABS and TPU materials to investigate which basic geometric surface and which material would be more suitable for textile-like materials in the fashion industry. This test was performed to measure the wearability of a fabric or surface.

The aim of the flexural strength (Figure 22b) test was to examine the drape on the human body when a textile-like surface is worn. In this test, six different samples were printed with ABS and TPU materials using three different basic geometric patterns, followed by the relevant research.

While applying these tests, the dimensions of specimens of 150 mm × 50 mm × 2 mm were accepted as adequate for testing on the dynamometer. Therefore, all samples were designed to be closest to these dimensions. Laboratory values of ambient temperature was 23 °C ± 2 °C and relative humidity of 45% ± 10%. Measurements were made according to the ISO 13934-1 test standard.

3 Results and discussion

In this study, mass, tensile stress and flexural strength of samples with different geometric surfaces produced in the same dimensions with ABS and TPU materials was analyzed, compared and interpreted.



a) b)
Figure 22: Photos of a) tensile test and b) flexural test

72 printed textile-like surfaces were obtained from 12 different models for tensile strength testing. The obtained surfaces were compared in two different ways with different geometric surfaces and different materials.

3.1 Production times of models and mass measurement results

For all 3D-printed geometric structures presented, the manufacturing time and mass of the structures were first analyzed.

Table 3 shows that the printing times of the designed models vary depending on the model and material. This is because ABS and TPU materials have different printing parameters. For this reason, an exact comparison of the printing times is not possible.

Table 4 and Figure 23 clearly show that all models printed with TPU are heavier than those printed with ABS. Although the models with TPU and ABS materials are all made in the same dimensions, the reason why the models printed with TPU are heavier is that TPU and ABS materials have different specific densities. TPU material has a higher spe-

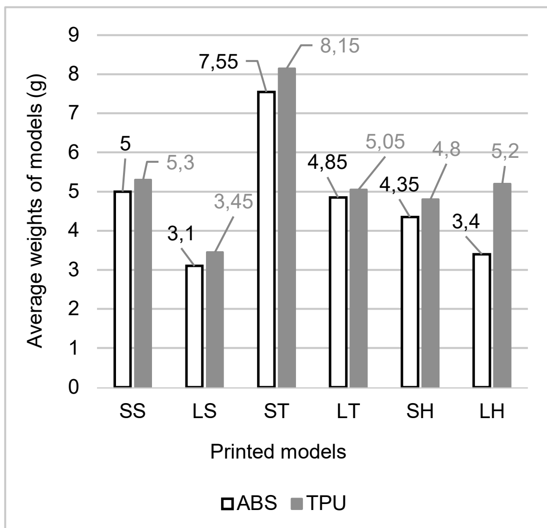


Figure 23: Average mass of models

Table 3: Production times of models

Geometric structure	Marked as	Production time with ABS (min)	Production time with TPU (min)
Small size hole square	SS	173	141
Large size hole square	LS	77	87
Small size hole triangle	ST	111	306
Large size hole triangle	LT	163	139
Small size hole hexagon	SH	164	126
Large size hole hexagon	LH	99	129

Table 4: Average weight of models

Geometric structure	Average weight and STDV of ABS models (g)	Average weight and STDV of TPU models (g)
SS	5.0 ± 0.21	5.3 ± 0.20
LS	3.1 ± 0.25	3.45 ± 0.21
ST	7.55 ± 0.28	8.15 ± 0.17
LT	4.85 ± 0.23	5.05 ± 0.20
SH	4.35 ± 0.27	4.8 ± 0.04
LH	3.4 ± 0.19	5.2 ± 0.26

cific gravity than ABS material. The density of TPU material is 1.15–1.17 g/cm^3, while the density of ABS material is 1.03–1.10 g/cm^3 [12, 13].
It is clearly seen that the large size hole square is the lightest and the small size hole triangle is the heaviest of samples produced using both materials.
Mass determination results provide important information on many performance properties, such as the strength, density, and softness of the material. At the same time, mass determination tests provide information about the density of textile surfaces [14].

3.2 Tensile strength test results

Maximum force applied to the samples, percentage of tensile strain (displacement) at maximum force and amount of displacement at maximum force are given in the Table 5 and 6, and Figures 24–26.
The tensile stress test results of six different samples printed with TPU material and created based on three different basic geometric patterns clearly shows that under maximum strength, hexagonal structure specimens have higher tensile stress performance than specimens produced in other structures. This is the same for hexagonal structures produced using both TPU and ABS materials. Since TPU material is more flexible than ABS material, the displacement percentages of the samples produced using TPU material under maximum force are quite high compared to ABS material. In the samples produced using TPU material, the highest displacement percentage was 317.53% under maximum force, while the highest value was obtained for ABS material, at 6.212%.
The displacement of the specimens at maximum force, tensile strain (displacement) at maximum force and maximum force at tensile stress were measured in this test. The speed of the measuring device was 025 mm/s.

Tensile strength results vary according to materials and sample structures. Since the material and basic geometric surface structure were investigated in this study, the samples were produced in the same dimensions and on the same model surfaces. The test results clearly show that the tensile stress (displacement) of TPU material at maximum strength demonstrated much higher values than ABS material.
Moreover, Figure 26 shows that the maximum force applied to ABS material is much higher than the maximum force applied to TPU material, since ABS material is much less flexible than TPU material.
Comparison of tensile strength results of samples with basic geometric structures produced using ABS material: LH > SH > ST > SS > LS > LT (Table 5).
Comparison of tensile strength results of samples with basic geometric structures produced using TPU material: LH > ST > SH > SS > LT > LS (Table 6).
It is clear that the hexagonal specimens have the highest tensile strength at both materials.

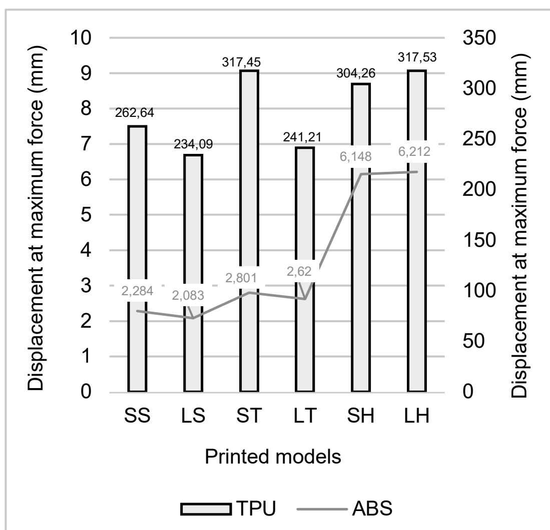


Figure 24: Displacement at maximum force

Table 5: Tensile strain test results applied to models produced using ABS

ABS models	Maximum force (N)	Tensile strain (displacement) at maximum force (%)	Displacement at maximum force (mm)
SS	674.858 ± 35.448	4.569 ± 0.704	2.284 ± 0.352
LS	435.340 ± 35.922	4.165 ± 0.407	2.083 ± 0.204
ST	766.462 ± 17.023	5.601 ± 0.402	2.801 ± 0.201
LT	437.367 ± 15.954	4.125 ± 0.448	2.062 ± 0.224
SH	310.827 ± 6.015	12.296 ± 1.824	6.148 ± 0.912
LH	194.244 ± 12.765	12.424 ± 1.872	6.212 ± 0.936

Table 6: Tensile strain test results applied to models produced using TPU

TPU models	Maximum force (N)	Tensile strain (displacement) at maximum force (%)	Displacement at maximum force (mm)
SS	382.696 ± 10.966	525.280 ± 10.448	262.640 ± 5.224
LS	231.116 ± 37.769	468.180 ± 76.292	234.090 ± 38.146
ST	556.948 ± 54.403	601.900 ± 69.924	300.450 ± 34.962
LT	273.418 ± 34.962	482.420 ± 4.052	241.210 ± 2.026
SH	331.192 ± 7.305	608.520 ± 25.904	304.260 ± 12.952
LH	355.691 ± 25.423	635.060 ± 16.080	317.530 ± 8.040

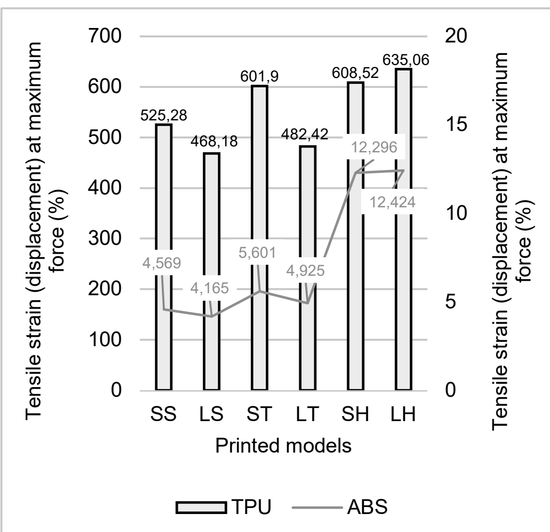


Figure 25: Tensile strain (displacement) at maximum force

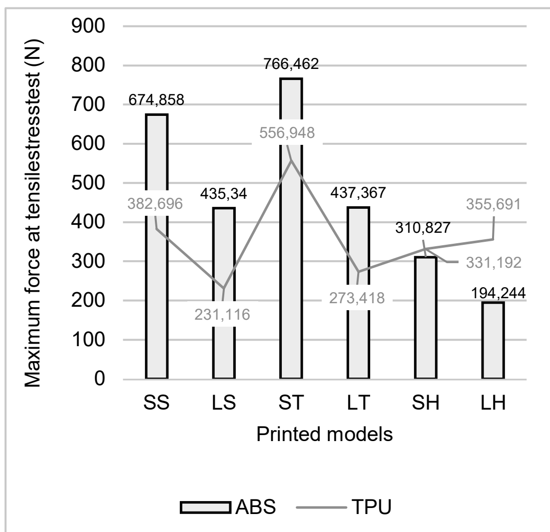


Figure 26: Maximum force at tensile stress test

Textile-like surfaces produced using different geometric shapes

According to Tables 5 and 6, the smaller the repeating pattern units on printed textile-like surfaces, the higher the tensile strength and vice versa: the larger the pattern, the harder the textile-like surface produced. If the patterns were printed in small repeat units, the mass of the models increased (Table 4).

As a result of the tests conducted in this study, the order of tensile strength of different geometric models made with both ABS and TPU materials is as follows: SH > ST > SS, LH > LT>LS.

Tables 5 and 6 clearly show that textile-like surfaces printed with a hexagonal pattern have a much higher tensile strength.

Hexagons are ubiquitous in nature, from the largest planets to microscopic compounds. The reason for this prevalence, however, is not because hexagons have a special edge, but because the simplest shape that can be created in nature is the circle, and flexible circles spontaneously transform into hexagons under pressure. From honeycombs to giant clouds on planets, from geological formations to snowflakes, every hexagon can be illuminated using purely scientific explanations. For millennia, scientists and philosophers thought the hexagon was the shape that would most efficiently fill a plane. However, this idea was discussed earlier. Moreover, at the end of the 19th century, the Belgian physicist Joseph Plateau was able to calculate that the forces on 120-degree foils are all in equilibrium and that this geometry is the most mechanically stable arrangement [15].

3.3 Flexural strength test results

Flexural strength test results are given in Tables 7 and 8, and on Figures 27–29.

TPU material has a higher flexibility than ABS material. For this reason, Figure 28 clearly shows that TPU material requires much less force to bend than ABS material.

When evaluating the flexural strength of models made using the two different materials, no direct correlation can be established between the flexural strengths of different shapes.

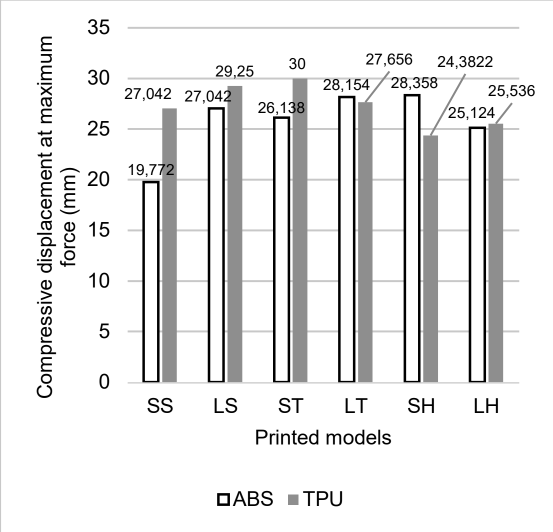


Figure 27: Compressive displacement at maximum force

Table 7: Flexural strength test results applied to models produced using ABS material

Models of ABS	Maximum force (N)	Compressive displacement at maximum force (mm)	Force at break (Standard) (N)
SS	9.112 ± 0.19	24.208 ± 2.24	8.364 ± 0.28
LS	5.341 ± 0.17	27.042 ± 3.96	5.140 ± 0.31
ST	12.743 ± 0.53	26.138 ± 2.83	11.933 ± 0.68
LT	8.386 ± 0.42	28.154 ± 0.72	7.438 ± 0.37
SH	5.744 ± 0.15	28.358 ± 3.84	5.297 ± 0.16
LH	4.786 ± 0.10	25.124 ± 1.09	4.537 ± 0.23

Table 8: Flexural strength test results applied to models produced using TPU material

Models of TPU	Maximum force (N)	Compressive displacement at Maximum Force (mm)	Force at break (Standard) (N)
SS	0.185 ± 0.01	27.042 ± 3.07	0.159 ± 0.01
LS	0.135 ± 0.01	29.250 ± 1.47	0.119 ± 0.00
ST	0.274 ± 0.01	30.000 ± 3.86	0.272 ± 0.03
LT	0.141 ± 0.00	27.656 ± 2.46	0.125 ± 0.01
SH	0.109 ± 0.01	24.822 ± 1.86	0.100 ± 0.01
LH	0.133 ± 0.01	25.536 ± 2.03	0.118 ± 2.03

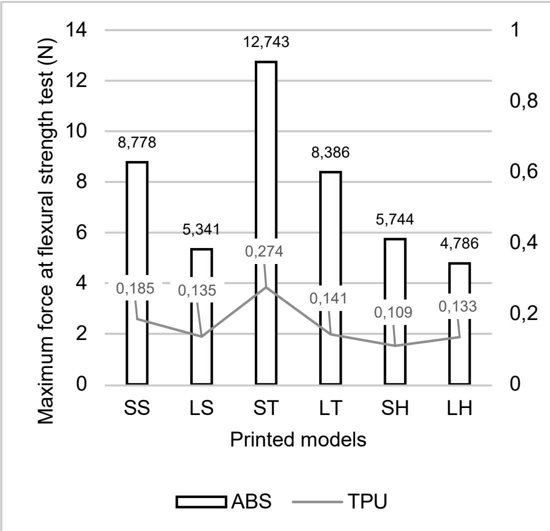


Figure 28: Maximum force at flexural strength test

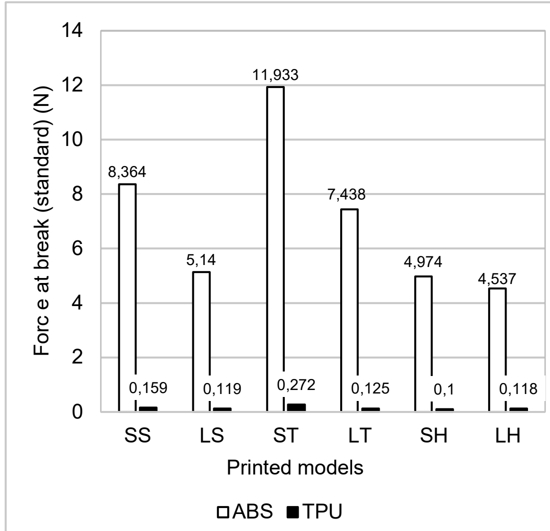


Figure 29: Force at break (standard)

4 Conclusion

3D printers are appearing in all aspects of our lives, including the textile and fashion industries. 3D printers, which have the potential to facilitate personalized production, are gaining momentum as the technology evolves. Manufacturing with 3D printers is an alternative to traditional manufacturing methods.

Defined as the manufacturing method of the 21st century, 3D printers allow the body to be wrapped like fabric, weaving together different shapes in different sizes. Textile designers can work with this technology as an alternative working method instead of traditional production methods.

For this article, six different patterns were designed using three different basic geometric shapes. A total of 72 patterns were made using six different models with two different materials. These patterns were subjected to mass, tensile strength and flexural strength tests. From the results of the tensile strength tests, it was determined that different geometric shapes affect tensile strength. Hexagonal structures have high values, while square structures have lower values. The hexagonal structures showed the highest resistance to the force applied to them when the tensile stress test was performed. This is due to the fact that the hexagons, because of their angle of 120°, were able to equally resist the force applied by all arms. Different models have an impact on the comfort of the products used in the textile-like material in fashion industries. The result in this case was that the hexagonal structures are more comfortable than others.

The results show that the tensile strength of TPU material is much higher than that of ABS material. In addition, textile-like surfaces made using TPU material have more flexibility and drape than textile-like surfaces made using ABS material.

Textile-like surfaces printed using TPU material have a softer feel than those made using ABS material. Therefore, textile-like surfaces made using TPU material are more suitable in terms of wearability. ABS material's hard handling, lower flexibility, and lack of drapability limit its use in the material in fashion industries.

However, ABS material can be used in the manufacture of accessories as an alternative material for the textile material and fashion industries, such as buckles, crown buttons, zippers, walking sticks, umbrella bags, fans, watch straps, etc.

The order of bending strength of the models made using ABS material according to their values under compression displacement at maximum force was as follows: shapes with small holes and shapes with large holes; triangle with small holes > square with small holes > hexagon with small holes, square with large holes > triangle with large holes > hexagon with large holes.

The order of bending strength of the models made using TPU material according to their values under compression displacement at maximum force was as follows: shapes with small holes and shapes with large holes; triangle with small holes > square with small holes > hexagon with small holes, square with large holes > triangle with large holes > hexagon with large holes.

No conclusion could be drawn from the results of the applied flexural strength tests, since the impact of shapes on flexural strength was not stable. However, comparing two different materials, the difference between the maximum forces can be clearly seen. According to the results of the bending strength test, we can conclude that the properties of the materials impact these test results rather than the moulds.

It can be seen from this study that, in the production of a wearable textile-like surface using 3D printers, the geometric shape of the unit patterns that form the surface and the size of the unit patterns affect the properties of the textile-like surface. In this study, three basic geometric shapes and two different materials (ABS and TPU) were used. It is therefore likely that the data from this study can serve as a reference for new studies when a textile-like surface with a geometric unit pattern is to be obtained.

References

1. AVCI, G., EREN, O., SEZER, H.K. Tekstil sektörüne eklemeli imalat yaklaşımı: 3B yazıcılar ile deneysel çalışma . In *Uluslararası Bilim, Teknoloji Ve Sosyal Bilimlerde Güncel Gelişmeler Sempozyumu, Ankara, Turkey*, 2019, 411–419.
2. ERBIYIKLI, N. Art and science in terms of textile and fashion design [online]. DergiPark Akademik [accessed 14 December 2022]. Available on World Wide Web: <https://dergipark.org.tr/tr/download/article-file/275338>.
3. YILDIRAN, M. Moda giyim sektöründe üç boyutlu yazıcılarla tasarım ve üretim. *Art-e Sanat Dergisi*, 2016, **9**(17), 155–172.
4. UYSAL, R., STUBBS, J.B. A new method of printing multi-material textiles by fused deposition modelling (FDM). *Tekstilec*, 2019, **62**(4), 248–257, doi: 10.14502/Tekstilec2019.62.248-257.
5. MELNIKOVA, R., EHRMANN, A., FINSTERBUSCH, K. 3D printing of textile-based structures by Fused Deposition Modelling (FDM) with different polymer materials. *IOP Conference Series: Materials Science and Engineering*, 2014, **62**(1), 1–7, doi: 0.1088/1757-899X/62/1/012018.
6. Comprehensive guide on Acrylonitrile Butadiene Styrene (ABS) [online]. Omnexus [accessed 11 August 2022]. Available on World Wide Web: <https://omnexus.specialchem.com/selection-guide/acrylonitrile-butadiene-styrene-abs-plastic>.
7. FILAMEON ABS HighFlow Filament [online]. FILAMEON [accessed 11 August 2022]. Available on World Wide Web: <https://www.filameon.com/urun/filameon-abs-filament/>.
8. Comprehensive Guide on Thermoplastic Polyurethanes (TPU) [online]. Omnexus [accessed 11 August 2022]. Available on World Wide Web: <https://omnexus.specialchem.com/selection-guide/thermoplastic-polyurethanes-tpu>.
9. FILAMEON TPU Filament [online]. FILAMEON [accessed 11 August 2022]. Available on World Wide Web: < https://www.filameon.com/urun/filameon-tpu-filament/>.
10. PARTSCH, L., VASSILIADIS, S., PAPAGEORGAS, P. 3D printed textile fabrics structures. In *5th International Istanbul Textile Congress 2015: Innovative Technologies "Inspire to Innovate", September 11th-12th 2015, Istanbul, Turkey*, 1–7.
11. REISS, D. *Complex processes and 3D printing*: BSc project. London : Imperial Collage London, 2013, 1–15.
12. ABS Plus. Safety data sheet [online]. Azurefilm [accessed 11 July 2022]. Available on World Wide Web: <https://www.azurefilm.com/media/uploads/Tehni%C4%8Dni%20listi/ABS/ABS_Plus_SDS.pdf>.
13. OĞULATA, R.T., KADEM, F.D. Prediction of regression analyses of fabric tensile strength of 100% cotton fabrics with yarn dyed in different constructions. *Textile and Apparel*, 2008, **18**(3), 185–191.
14. Flexible 98A TDS [online]. Azurefilm [accessed 11 July 2022]. Available on World Wide Web: <https://www.azurefilm.com/media/uploads/Tehni%C4%8Dni%20listi/FLEXIBLE/Flexible_98A_TDS.pdf>.
15. Doğada Altıgen Geometri Neden Bu Kadar Yaygın? (Why ıs hexagonal geometry so common in nature?) [online]. Evrim Ağacı [accessed 12 July 2022]. Available on World Wide Web: <https://evrimagaci.org/dogada-altigen-geometri-neden-bu-kadar-yaygin-11666>.
16. ÖZGÜN, C.A. N., ARABACI, H. 3 boyutlu yazicilarin moda aksesuarlari üretiminde kullanilmasi (The usage of 3D printers in the production of fashion accessories). *International Journal of 3D Printing Technologies and Digital Industry*, 2021, **5**(3), 445–456.
17. BULAT, F. BAŞARAN, F.N. Tekstil tasariminda yenilikçi yaklaşimlar: 3B yazicilarla deneysel çalişmalar (Innovative approaches in textile design: experimental practices with 3D printers). *Kesit Akademi Dergisi*, 2018, **4**(15) , 257–273.